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Pulsed probe diagnostics of a high-current low-pressure discharge in crossed E×H fields

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Abstract. The measurement results for electron temperature, plasma density and emission ability of a high-current low-pressure discharge in crossed **E×H** fields by pulsed probe diagnostics method are given in this article.

1. Introduction

The intensive investigations of low-pressure discharges in crossed **E×H** fields are at present witnessed thanks to the later wide use in technological magnetron devices to deposit nanostructured coatings onto various materials including thermo-unstable such as *lavsan* (polyethylene terephthalate), fur, paper, plastics and others by employing both high-current pulsed magnetron sputtering systems and high rate ion stimulated etching aimed at polymers surface development [1].

Experimental studies of quasi-steady high-current discharges in crossed **E×H** fields in various gases (Ar, N_2, H_2, SF_6) and gas mixtures (Ar/SF_6, Ar/O_2) atmospheres at pressures from 10^{-2} up to 5 Torr under different configurations and magnitudes of the magnetic field have shown the existence of a stable discharge mode without the later being converted into an arc under high current densities. This is the so-called high-current diffuse discharge [2] operating in the current range of 10–2000 A at a cathode current density of up to 90 A/cm^2 and a constant discharge voltage of 75–140 V, the discharge duration being longer than 1 ms; no current contraction being observed in both the discharge plasma and the cathode sheath. Typical current-voltage characteristics of a low-pressure discharge in a magnetic field are shown in figure 1, where a high-current diffuse discharge (3) occupies an intermediate position between the high-current pulsed magnetron discharge (2) and the arc discharge (4).
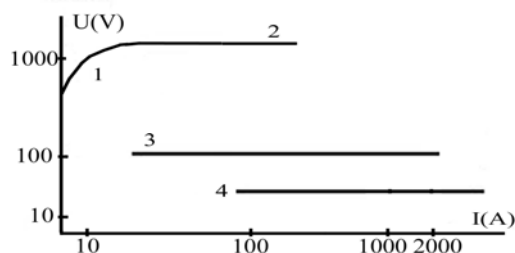

Figure 1. Typical current-voltage characteristics of low-pressure discharge in a magnetic field: 1 – DC magnetron discharge, 2 – high-current pulsed magnetron discharge, 3 – high-current diffuse discharge, 4 – arc discharge.

Since a general theory of the mechanisms governing this type of discharge is still lacking, it is very important to study the parameters (electron temperature, plasma density and emission ability) of the discharge plasma and the cathode sheath. The knowledge of these parameters will allow us to control the processes of coating deposition and surfaces etching.

2. Experimental setup and measurement system

The study the high-current low-pressure discharge in crossed **E**×**H** field has been carried out by using two types of devices: a planar magnetron (figure 2) and a system with profiled electrodes (figure 3).
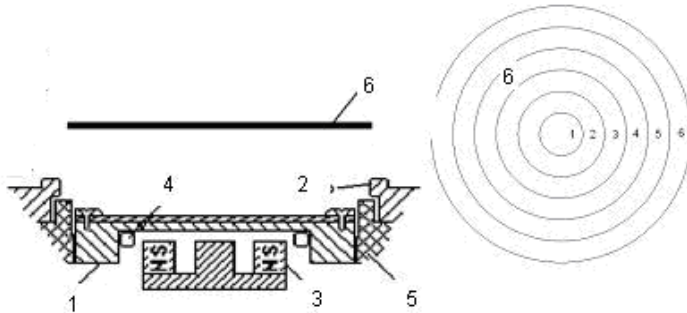

Figure 2. The discharge device "planar magnetron": 1 – cathode, 2 – anode, 3 – magnetic system, 4 – water cooling, 5 – insulator, 6 – probe-collector.
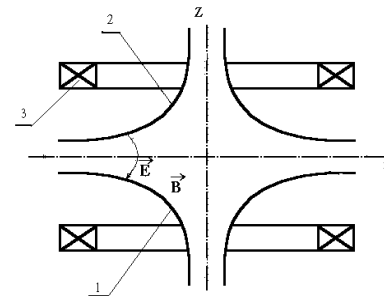
Figure 3. The discharge device with profiled electrodes: 1 – cathode, 2 – anode, 3 – magnetic system.

The planar magnetron consists of a plane cathode 120 mm in diameter and ring-shaped anode 160 mm in diameter. The electrodes are immersed in a magnetic field of annular permanent magnets. The discharge has an annular shape and is closely adjacent to the cathode. The maximum of the magnetic field radial component B at the cathode surface is 1200 G. The cathode is made of Cu or Al placed on a cooled surface. The anode is made of stainless steel.

The discharge device with profiled electrodes consists of two hollow axis-symmetric electrodes and a magnetic system. These electrodes 120 mm in diameter are placed at a distance of 10 mm from one another in a cusp magnetic field produced by two oppositely directed coils. The electrode profile coincides with a magnetic field line to secure the perpendicularity of electric and magnetic fields the entire electrode surface. The ratio of the maximum magnetic field at the symmetry axis, $B_{max}(z, 0)$, to the maximum magnetic field in the symmetry plane, $B_{max}(0, r)$, is $B_{max}(z, 0)/B_{max}(0, r) \cong 3$. The magnetic induction varies from 0 to 1000 G by changing the current in the coils.

To ignite a high-current diffuse discharge, a high-voltage pulse from a forming line, consisting of 19 LC section with a total stored energy of 6.3 kJ, is applied to the discharge gap, which is preionized by a steady-state DC magnetron discharge.

The voltage and current of a high-current diffuse discharge are measured by using an ohmic divider and a Rogowski coil (operating as a current transformer), respectively.

The pulsed probe diagnostics scheme of dense gas-discharge plasma includes a probe, a sweep generator, and a measurement system [3]. The probe, in case of the "profiled electrodes", is a conventional cylindrical probe consisting of a stainless steel rod partially covered by a ceramic insulator: the probe diameter is $a = 0.6$ mm, and the area of the working surface is $S = 16$ mm^2. The probe-collector is used for plasma emission ability measurements (in the planar magnetron). The probe-collector is a plane disk 110 mm in diameter consisting of *textolite* covered by an Cu foil. The choice of the probe-collector diameter is linked with the necessity to have the probe covering all the discharge area. The probe surface is divided into 6 annular zones with 1 cm pitch. The probes are located in the center of the electrodes system, on the distances where the magnetic field is of

minimum. This allows to process and interpret the results obtained while neglecting the effect of the magnetic field.

3. Experimental results

First, the pulsed plasma parameters measurements of low-pressure high-current diffuse discharge in crossed $\mathbf{E} \times \mathbf{H}$ fields were carried out in the device with profiled electrodes. The discharge parameters were: magnetic field $B = 0$–1000 G, pressure $p = 10^{-2} - 1$ Torr, and the discharge current of up to 1500 A. The working gas was argon. Pre-ionization was produced by the DC magnetron discharge with a current of up to 200 mA.

Based on the probe measurements the plasma parameters were calculated. The obtained dependences of the ion density in the center of the system on the current of a quasi steady high-current diffuse discharge for different values of the gas pressure of up to 10^{-2} Torr and magnetic field showed that the plasma density increases almost linearly as the discharge current (figure 4).
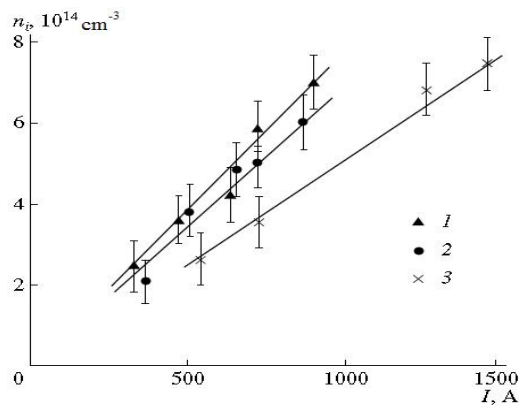
Figure 4. Dependence of plasma density on a discharge current in the discharge device with profiled electrodes at conditions: $B = 800$ G, Ar: $1 - p = 0.5$ Torr, $2 - p = 0.3$ Torr, $3 - p = 0.1$ Torr.
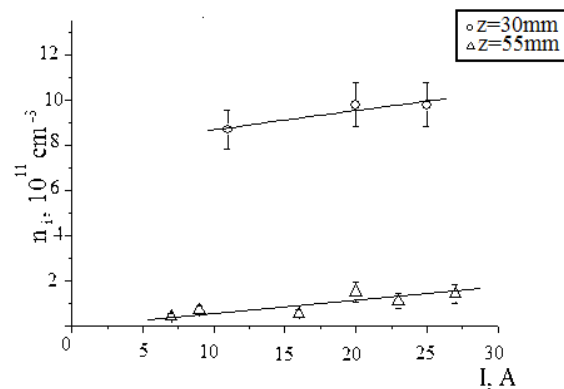
Figure 5. Dependence of plasma density on a discharge current in the planar magnetron at the conditions: $p = 8 \times 10^{-3}$ Torr, Ar/Air in proportions 7/1.

The electron temperature was $3-8$ eV. In this case the density of the probe ion saturation current was up to 15 A/cm^2. As the gas pressure in the discharge gap grows the ion density increases and the electron temperature decreases.

Second, the pulsed plasma parameters of high-current diffuse discharge were measured in the planar magnetron. The discharge parameters were magnetic field $B = 0$–1200 G and the discharge current of up to 30 A. The working gas was gas mixture Ar/Air in proportions 7/1. Using the Al cathode in the oxygen-containing gas mixture allowed us to lower ion current on the cathode, which was necessary for discharge maintenance and, hence, to reduce high-current diffuse discharge pressure down to 8×10^{-3} Torr. Pre-ionization was produced by the DC magnetron discharge with a current of up to 100 mA. Measurements were carried out on distances of 30 mm and 55 mm from cathode surface. The voltage pulse was applied to the probe with a time delay of $100-1000$ μs with respect to the beginning of the pulsed discharge. The electron temperature and the plasma density were measured after having got the quasi steady high-current discharge. The obtained dependences of the plasma density on a discharge current are presented on figure 5. It was seen that the plasma density also increases almost linearly as the discharge current and the distance from cathode surface. At the same time the electron temperature obtained was $3-8$ eV. The radial distribution of the plasma density depending on the distance from an axis of the system is presented on figure 6.
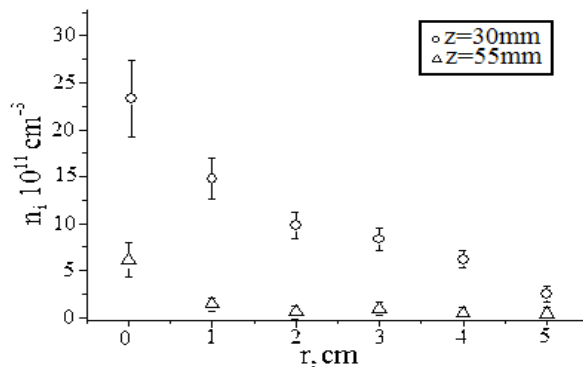
Figure 6. Dependence of the plasma density on the distance from a system axis in the planar magnetron at the conditions: $p = 8\times10^{-3}$ Torr, Ar/Air in proportions 7/1, $I = 30$ A.

The measurements of the probe ion saturations current showed that the emittance of the high-current diffuse discharge with the Al cathode in the oxygen-containing gas mixture can reach $0.003-0.5$ A/cm^2 depending on the probe-collector zone. The maximum ion saturation current was observed in the probe centre and fell down to its borders.

On the basis of the plasma obtained and discharge parameters, we estimated: Debye length $r_d = 8\times10^{-4}$ cm, thickness of the cathode layers $d_l = 0.09$ cm, mean length of electron free path in the electron – atom collisions $\lambda = 10$ cm, and height of the electron trajectory above the cathode surface $h = 0.3$ cm. The results reached have shown that the cathode layer of the given discharge is non-collisional and the absence of visible cathode spot traces on the cathode surface.

4. Conclusion

High-current low-pressure diffuse discharge inside crossed **E×H** fields with Al cathode placed in oxygen-containing mixture was investigated. The established operations modes are of practical outcome in developing new technologies in particular for forming Al structured surfaces.

Pulsed probe measurements of the plasma parameters for low-pressure high-current diffuse discharge in crossed **E×H** fields have shown the presence of a dense plasma (plasma density up to 10^{15} cm^{-3}) providing realization of a non-collisional cathode layer mode that corresponds to the concept of thermal ionization mechanism.

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